PIV for Turbomachinery Applications

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ABSTRACT

Particle Imaging Velocimetry (PIV) is emerging as a powerful measurement technique which can be used as an alternative or complementary approach to Laser Doppler Velocimetry (LDV) in a wide range of research applications. The instantaneous planar velocity measurements obtained with PIV make it an attractive technique for use in the study of the complex flow fields encountered in turbomachinery. The data acquired offer several advantages over traditional LDV data: higher accuracy; multiple measurement points and the ability to study both transient and steady state flow phenomena. Many of the same issues encountered in the application of LDV techniques to rotating machinery apply in the application of PIV. Techniques for optical access, light sheet delivery and particulate seeding are discussed. Preliminary results from the successful application of the PIV technique to a transonic axial compressor are presented.

Keywords: Particle Imaging Velocimetry, Rotating Machinery, Turbomachinery, Compressor, Transonic, Correlation processing, Light sheet, Periscope

INTRODUCTION

Turbomachines are used in a wide variety of engineering applications for power generation, pumping and aeropropulsion. The need to reduce acquisition and operating costs of aeropropulsion systems drives the effort to improve propulsion system performance. Improving the efficiency in turbomachines requires understanding the flow phenomena occurring within rotating machinery. Detailed investigation of flow fields within rotating machinery have been performed using Laser Doppler Velocimetry (LDV) for the last 25 years. The current state of the art in computational design tools deals with time averaged flow in turbomachinery blade rows (Ucer, 1994). LDV measurements are time and ensemble averaged over all of the blade passages in a rotating machine (Skoch et al., 1997, Strazisar, 1986, O'Rourke and Artt, 1994). Hence, LDV results are well suited for comparison to CFD predictions of the averaged flow fields.

Although average flow field measurements provide a great deal of insight into the performance of the machines, there are many unsteady flow phenomena occurring in the complex flow fields encountered in turbomachines which may significantly impact the steady state flow. The ultimate measurement technique would instantaneously measure 3-components of velocity in a 3-D volume at a high repetition rate. A series of instantaneous flow field measurements could be averaged together to compute the average flow field quantities, yet still offer the researcher instantaneous images of the flow field behavior. Holographic techniques are closest to serving as the panacea previously described for measuring all points in the flow simultaneously; however, holographic techniques have yet to mature to the point where their application to the harsh turbomachinery environment is practical (Barnhardt et al., 1994, Cha, et al. 1993).

In lieu of the ultimate system, Particle Imaging Velocimetry (PIV) appears to be the next best technique. Recent advances are leading to the emergence of PIV as a powerful velocity measurement technique which can be used as an alternative or complementary approach to LDV in a wide range of research applications. Refined data processing techniques and continuous increases in computational power have made PIV a more widely available and practical measurement technique. For a general overview of the various perturbations of the PIV technique see Adrian, 1986 and Grant, 1997. PIV is a planar measurement technique wherein a pulsed laser light sheet is used to illuminate a flow field seeded with tracer particles small enough to accurately follow the flow. The positions of the particles are recorded on either photographic film or digital CCD cameras at each instant the light sheet is pulsed. The data processing consists of either determining the average displacement of the particles over a small interrogation region in the image or the individual particle displacements between pulses of the light sheet. Knowledge of the time interval between light sheet pulses then permits computation of the flow velocity. Different data processing schemes are employed depending on the number of exposures per frame and the seed particle concentration (Keane and Adrian, 1993, Wernet, 1995). While each technique has some inherent benefits, the appropriate choice depends on the characteristics of the flow and recorded image constraints. The purpose of this work is to describe and identify the important features/obstacles encountered when attempting to make instantaneous velocity measurements in a high speed, transonic axial or centrifugal compressor.

Numerous researchers have employed various PIV techniques to study the unsteady flows in rotating machines. Paone et al., 1988, used PIV to make blade-to-blade plane velocity measurements in a centrifugal compressor. Although not a rotating machine application, Bryanston-Cross et al, 1992 described photographic PIV measurements obtained in a transonic turbine cascade rig. The light sheet illumination was introduced via a 8.0 mm diameter hollow turbulence generating bar already part of the experimental rig. Post et al., 1991 also discuss PIV measurements in a turbine cascade using photographic film. In this work color film was employed and the light sheet pulses were of two distinct wavelengths, which then permitted cross-correlation data reduction of the electronically digitized photographs. Shepherd et al, 1994 used photographic PIV to study the flows inside both centrifugal and axial fans. The test setups employed water as the working fluid and hence were restricted to low rotational speeds. Tisserant and Breugelmans, 1997 used a digital PIV technique to measure the flow field in a subsonic (30-70 m/s, 3000-6000rpm) axial fan. They noted that an optical periscope type probe (similar to that used by Bryanston-Cross, et al 1992) is required for introducing the light sheet into the flow and that out-of-plane velocities are sometimes significant, causing a loss of correlation of the in-plane velocities. Rothlübbers et al, 1996, used digital PIV to study the flow in a radial pump. Low seed particle concentrations were identified as not suitable for rotating machine studies, where high spatial resolution measurements are required. Oldenburg and Pap, 1996, used a digital PIV setup to investigate the flow field in the impeller and volute of a centrifugal pump. The lab scale facility used water as the working fluid and a transparent impeller. Several studies have been conducted utilizing PIV to analyze the flow field induced by rotating disks (Zhou and Garner, 1996, Prasad and Adrian, 1992, Westergaard et al, 1992). All of these studies were water based systems and did not suffer the difficulties encountered from flare light scattering off of blade surfaces.

Cogineni and Goss, 1997 have described a two color digital PIV technique which should be applicable to turbomachinery applications. The two color digital PIV technique has been demonstrated on a lab scale shrouded fan rig. A high resolution (3000×2000 pixel) single CCD sensor color camera is employed to record the particle images at two instances in time on a single CCD image frame using red and green illumination pulses. A special algorithm is used to separate the color planes so that the red and green particle image exposures can be used in a cross-correlation data reduction operation. It would appear that the recorded particle image must span at least 2 to 3 pixels in order in order for the color separation algorithm to unambiguously determine the particle's color. Due to the architecture of the sensor and the additional processing algorithms used to separate the color planes, this technique does not appear to offer any significant advantages over a black and white 1000×1000 pixel CCD array which is capable of recording a pair of single exposure image frames at a short time interval apart (< 1 μsec).

Most of the works listed above are laboratory scale facilities, operating at low RPM. In these cases, the experimental hardware (impeller and/or casing) are easily manufactured from transparent materials to simplify both the introduction of the light sheet and the optical access for the recording system. The work of Bryanston-Cross, et al, 1992, Shepherd et al, 1995, Cogineni and Goss, 1997 and Tisserant and Breugelmans, 1997 employed PIV in near "real world" scale facilities. These systems used air as the working fluid and operated at moderate to transonic speeds. In these more realistic experimental setups, the hardware is manufactured from metal, hindering optical access. Special consideration must be given to the introduction of the light sheet into the fluid so that the flow field is undisturbed and the measurement plane is located in a region of interest and aligned with the dominant flow direction. Some work has been reported on the development of fiber optic delivery systems for high energy laser systems. Anderson et al, 1996 describe a fiber bundle system for delivering 20 mJ/pulse second harmonic Nd:YAG laser pulses for use in combustion studies. The practicality of using fiber bundles and other light sheet delivery system options will be discussed in the text.

Finally, we will discuss the successful application of digital PIV to a transonic compressor. Measurements have been obtained in a single stage 50.8 cm diameter transonic axial compressor facility at NASA Lewis. The sample measurements were obtained in the blade-to-blade rotor passage at a rotational speed of 17,128 rpm using a commercial PIV system. A special optical periscope probe was used to generate and introduce the light sheet into the flow. A brief description of the optical setup and some preliminary results are presented.

OPTICAL ACCESS

Obtaining optical access to the flow field is never a trivial issue in rotating machine applications since the casing through which the measurements are to be made is cylindrical. Ideally, the optical access port will permit the light scattered from particulates in the flow to be collected by the recording system without significantly disturbing the flow. Matching the optical access port to the curvature of the casing introduces astigmatism or other optical distortions into the collected image. The optical access port must be at least as large as the measurement region size if measurements are to be made over constant sized regions from the rotor hub to the blade tip. For a fixed window size, a larger measurement plane can be collected near the hub, whereas at the blade tip the measurement region size is fixed by the optical port dimensions.

Backscatter LDV systems are reasonably well suited for the small optical access ports typically employed in rotating machine applications. The backscatter LDV systems require only a single optical access port. However, the standard PIV technique requires that the light scattered by the particles traversing the light sheet be collected at 90° from the plane of the light sheet. Hence, the light sheet must be introduced either upstream or downstream from the optical access port and directed along the flow direction. Depending on the geometry and size of the facility, introducing the light sheet into the flow may be difficult.

Some of the work done in stereoscopic PIV techniques may prove useful for restricted access PIV applications (Gauthier and Riethmuller, 1988, Prasad and Adrian, 1992, Hinsch, 1995, Wernet, 1996). There are basically two optical configurations used in stereo viewing PIV: lens displacement (where the two camera systems are both perpendicular to the plane of the light sheet); and tilted lens (where both camera systems are oriented at an inclined angle to the plane of the light sheet). Here we will concentrate only on the tilted lens configuration. If the Scheimpflug condition is satisfied in the tilted camera/lens PIV configuration, then all points on the object plane will be in focus on the image plane (Wernet, 1996). However, perspective distortion is introduced due to the tilted object and image planes, see figure 1a. The amount of perspective distortion is proportional to the image magnification and viewing angle relative to the illumination plane. If the light sheet and recording system are configured as in figure 1b, then 3-component, planar PIV measurements can be obtained through either a single optical access port or two closely spaced small optical access ports. The resulting perspective distortion is easily corrected digitally by the computer after the data processing, with the assumption that the distortion over each interrogation region in the PIV image is constant (Wernet, 1996). In this configuration, the light sheet bisects the axis of the two camera systems and enters through the same optical access port used to collect the light scattered from the particles in the flow. The primary flow direction is perpendicular to the plane of the light sheet rather than aligned with the plane of the light sheet. The light sheet thickness has to be increased (~ 2 mm) in order for two records of the particle position to be recorded. The oblique viewing direction from only one camera combined with the thick light sheet would introduce velocity magnitude errors; however, by using the in-plane velocity estimates from the two camera views to compute the 3-component planar velocity field, these errors can be minimized or eliminated.

If the light sheet can be introduced into the flow either upstream or downstream from the measurement location so that the light sheet is aligned with the primary flow direction, then the two camera stereo viewing optical arrangement depicted in figure 1c can be employed. In this configuration a standard 1 mm thick light sheet is used. Again, as described above, all three velocity components of the particulates traversing the light sheet are computed from the two camera views with minimal errors resulting from the oblique viewing.

LIGHT SHEET DELIVERY TECHNIQUES

Due to the high rotational speeds typically encountered in aerodynamic turbomachinery, pulsed light sources are required to provide sufficient light energy in a short time interval to record an unblurred image of the particles entrained in the flow. Two laser systems having the required properties for PIV image recording at high speeds are the Nd:YAG and

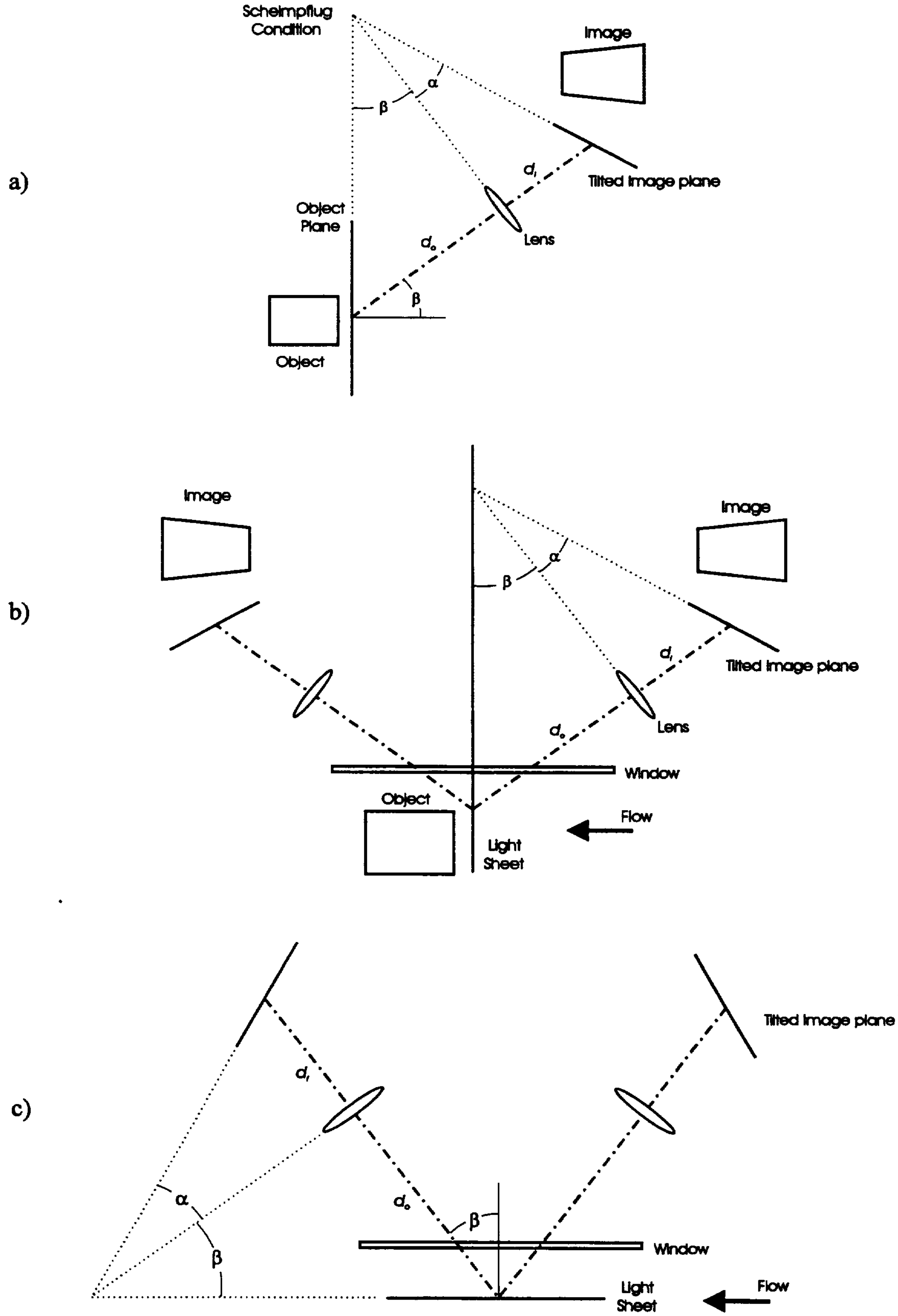

Figure 1: a) Optical system employing Scheimpflug condition, note distortion in recorded image; b) Single optical access port stereo viewing PIV optical configuration where the light sheet bisects the optical system; c) Stereo viewing optical configuration with light sheet perpendicular to the bisector of the optical system.

Ruby lasers. Both systems offer high pulse energy (~100mJ/pulse) and the short pulse lengths (<30 nsec) required for accurate recording of the particle images.

If the single optical access port configuration discussed above is not feasible, then a separate light sheet delivery system must be considered. If the rotating machine under study has a large cross sectional area and an easily accessible region upstream of the rotor then the light sheet forming optics can be mounted in this region. Care must be taken to insure that the light sheet optics do not disturb the stream tube feeding the blade passage under study. If the propagation direction of the light sheet is aligned with the stagger angle of the blades and the optics are located sufficiently far upstream, then the flow in the region of interest will not be disturbed, see figure 2. One potential problem with this configuration is contamination of the optics with seed material. A protective housing and/or a purge air stream may be required to keep the sheet forming optics from becoming contaminated. The laser beam must be delivered into the rig and directed down the center of the light sheet forming optics via a series of mirrors. Maintaining alignment of the light sheet optics when moving the light sheet to other spanwise positions is not a simple task.

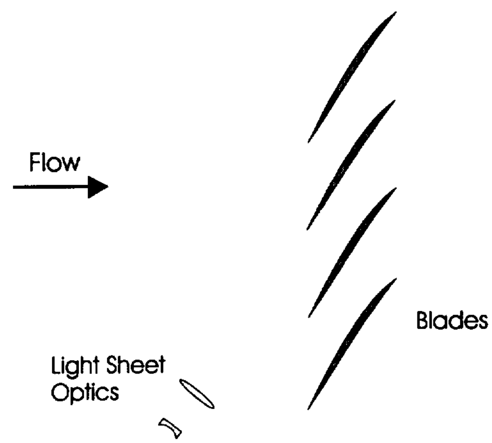

Figure 2: Unprotected light sheet optical system placed in the flow upstream of the rotor.

Fiber optics have been used to make LDV systems portable and easily mounted in what once would have been very difficult installations. The use of fiber optics for PIV light sheet delivery would seem a natural progression. However, the high pulse energies associated with Nd:YAG lasers precludes the use of individual multi-mode fibers. Some success has been achieved using fiber bundles for laser pulse energies up to 20 mJ (Anderson, et al, 1996). The fiber bundle permits a flexible connection from the laser to the light sheet forming optics inside the turbomachinery rig. It is conceivable that the fiber bundle could be formed into a linear array of fibers, which when coupled to a cylindrical lens could easily form the necessary light sheet illumination. However, breaking the fibers out of the tightly bound bundle into a linear array would most likely create an unacceptably large flow blockage/disturbance upstream of the measurement location.

A very compact light sheet delivery system can be constructed using a periscope type configuration such as the one shown in figure 3a. The pulsed Nd:YAG beam is directed down the bore of the tube which contains light sheet forming optics and a 90° turning mirror. The light sheet exits the probe through a window which keeps the optics inside the probe protected from contamination by the seed material. An implementation of this design is shown in operation in figure 3b. When utilizing the periscope probe, the small diameter tube (~12 mm) is inserted through the compressor casing upstream of the measurement location, see figure 3c. Moving the probe in and out through the casing changes the span wise location of the illumination plane. In order to align the propagation direction of the light sheet along the blade stagger angle, the light sheet probe is inserted below the horizontal rig centerline. This insertion location ensures that the light sheet probe does not disturb the flow upstream of the actual measurement location. The bulkhead feed through is designed so that the light sheet generating probe is oriented horizontally, even though the entrance point through the rig casing window is below the horizontal centerline of the rig. Maintaining a horizontal entry ensures that the plane of the light sheet will remain parallel with the axis of the compressor, simplifying the recording system requirements.

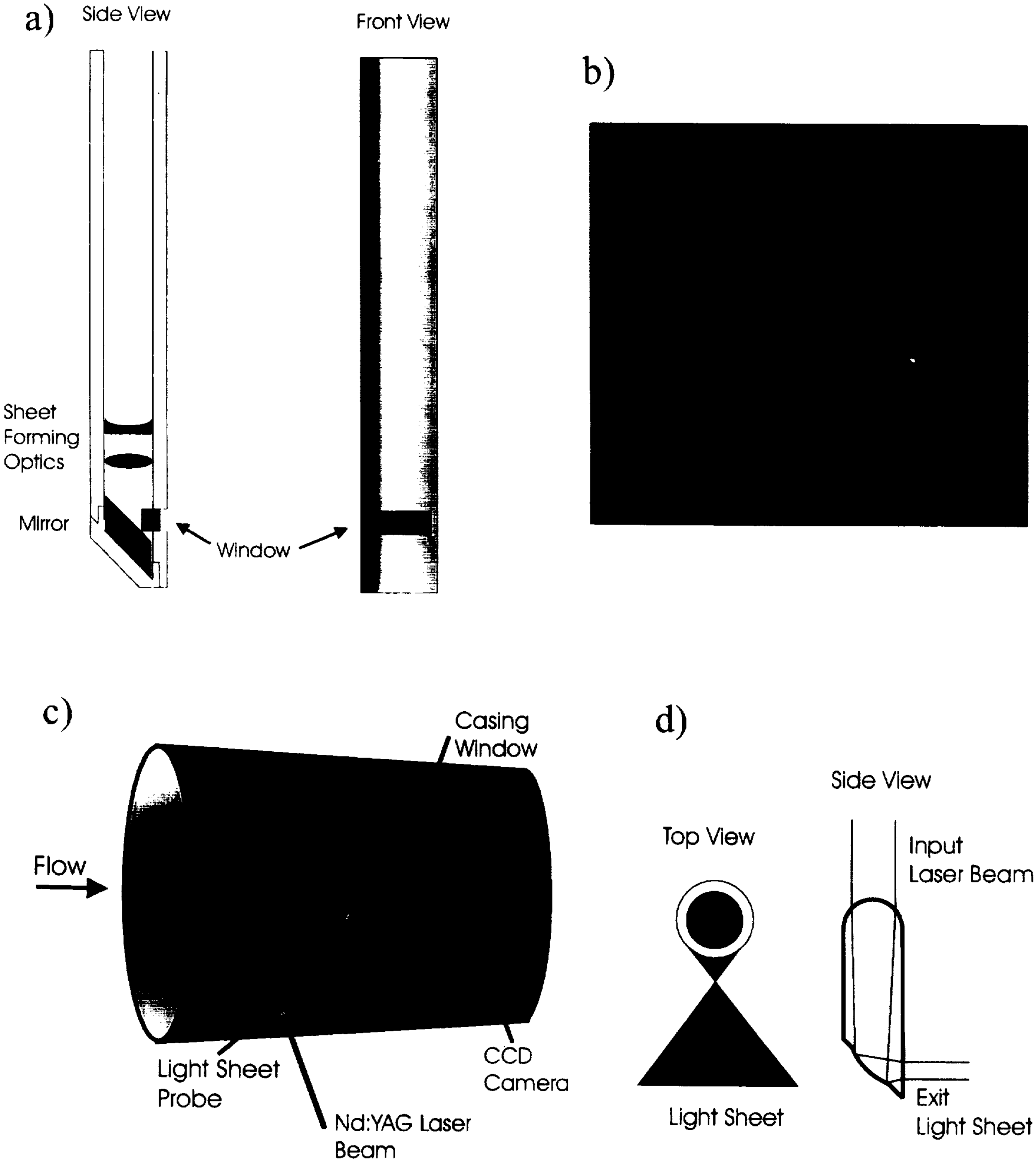

Figure 3: a) Cut away view of the light sheet periscope probe showing lenses, mirror and exit window;
b) Picture of light sheet probe in operation where the light sheet emerges from the probe horizontally, note the articulated arm which directs the Nd:YAG laser beam down the bore of the periscope probe;
c) Diagram indicating light sheet insertion into compressor rig, location of casing window and CCD camera;
d) Single Sol-Gel optic to perform light sheet forming operation of cylindrical, spherical lenses and turning mirror.

A possible variation on the light periscope probe involves the replacement of the light sheet forming optics and turning mirror with a single Sol-Gel optic, as shown in figure 3d (Nogués and Hunt, 1995). The single optic shown in figure 3d replaces the spherical lens, cylindrical lens and turning mirror in a typical light sheet forming optical setup. The curved entrance end of the Sol-Gel optic acts as a lens to focus the beam. The beam reflects off of the bottom surface oriented at 45° via total internal reflection. The concave shape in the bottom surface acts as an additional focusing element to further refine the thickness of the resulting light sheet in the vertical plane. The cylindrical shape of the optic acts as a positive cylindrical lens. As the beam emerges from the optic it comes to a focus and then expands continuously in the horizontal plane. The advantages of the Sol-Gel optic are the compactness of the light sheet forming optics and the reduction in the number of optical components. Two drawbacks on the design are the high laser energy density created inside the probe as the beam comes to a focus in the vertical plane and the possibility of breaking down the air at the focus point formed in the horizontal plane just outside of the optic. Sol-Gel optics have essentially the same damage threshold as fused silica optics and are usable up to laser energy densities of approximately 1J/cm^2 for 1 ns pulses.

In either of these periscope probe configurations, directing the pulsed laser beam down the bore of the periscope tube is extremely challenging. In lieu of using a fiber optic bundle to couple the pulsed laser beam to the periscope probe, an articulated arm with mirror joints can be used to easily and reliably direct the beam down the bore of the probe, see figure 3b. Articulated light arms for Nd:YAG laser beam delivery are commercially available from several commercial PIV vendors. Use of the light arm simplifies the coupling of the Nd:YAG beam to the periscope and also adds a level of safety to the installation since the beam is entirely enclosed outside of the rig. The light sheet delivery probe depicted in figure 3a has been successfully used by the author to deliver 125 mJ pulsed illumination into a compressor facility. The full energy range of the laser is available by using the articulated arm, as opposed to the maximum per pulse energy limitations imposed by the fiber delivery systems.

SEEDING

A uniform and sufficiently high concentration of flow seeding is the most critical element in any PIV experiment. If the number of particles recorded on the CCD image frame is too low, then correlation techniques cannot be applied, although particle tracking could still be utilized. As discussed previously, particle tracking does not typically provide a sufficient density of measurements necessary to adequately characterize the complex flows encountered in turbomachinery (Rothlübbers et al, 1996). However, provided the particle concentration is sufficiently high to support correlation computations particle tracking can be combined with the correlation technique results to provide high spatial resolution velocity estimates (Keane and Adrian, 1993, Wernet, 1995).

In some instances, a facility that was previously used for obtaining LDV measurements of the flow field velocity will be a candidate for application of PIV. The advantage to this migration is that there will be an established technique used in the facility for seeding the flow field with tracer particles that adequately follow the flow. However, a potential problem in utilizing a facility which was previously used for LDV measurements is that the amount of seed particles introduced into the flow will most likely be too low.

An LDV experiment utilizing a probe volume that is 100 μm high by 500 μm long to measure a 200 m/s flow may achieve a data rate of 2KHz. This measurement rate is obtained by using a seed particle concentration of 0.2 particles/mm^3. Conversely, in a digital PIV experiment where the field of view is 50×50 mm (yielding a spatial resolution of about 50 μm/pixel), the light sheet thickness is 1 mm, and the interrogation region size is 32×32 pixels, the required seed particle concentration so that there are 15 particles per interrogation region(or 15 particle pairs for double exposure image capture) is 6 particles/mm^3. Hence, the seeding requirements for PIV are more than an order of magnitude higher than that required for LDV.

The choice of seed material depends upon the experience and past successes in the flow facility under study. For transonic flows and above, sub-micron particles are required for accurately following the flow. Two very common seeding materials are olive oil and Polystyrene Latex Spheres (PSL) (Meyers, 1991, Nichols, 1987). Both materials are introduced using an atomizer in the plenum section of the facility. For higher temperature applications (>200 C), refractory seed materials can be used. Metal oxide particulates have a higher specific gravity than PSL or olive oil, therefore, their flow following ability is limited in highly accelerating and decelerating flows. Special preparation of metal oxide powders in ethanol or water dispersions are required to achieve stable dispersion in order to provide good quality seeding (Wernet, et al., 1994).

It is unlikely that a seeding system used to seed an entire large scale facility for LDV measurements would provide a sufficient amount of seed for PIV measurements. Instead, a higher probability of success will be achieved if the seed material can be introduced locally near the measurement plane. A multiple jet atomizing seeding system employing smoke juice feeding a small diameter tube through the rig casing many tube diameters (> 50) upstream of the measurement location has been successfully employed by the author to provide sufficient seed particle concentrations for correlation processing of the collected PIV images. The normal free stream turbulence intensity in the LeRC transonic compressor is approximately 2-3% hence, the seed tube disturbance on the upstream flow field is negligible.

TIMING

Acquisition of PIV imagery from rotating machines requires the use of an accurate time base for precise laser firing and camera exposure. In many cases the average flow qualities as well as the instantaneous flow field features are required to obtain a comprehensive understanding of the rotor blade performance. Hence, several hundred image acquisitions may be required so that mean quantities can be computed. Each image must be exposed at the same rotor circumferential position in order for the calculated velocity field grids on each image frame to be averaged together without interpolation or image shifting.

Again, the previous instrumentation employed for LDV measurements can be utilized for PIV measurements in rotating machines. Shaft angle encoding is not required for PIV since a single image or image pair is required in any given revolution of the rotor; therefore, only a once per rev signal is required for PIV measurements. Using the location of the once-per-rev sensor on the rotor, the rotational speed of the rotor and rotor diameter one can calculate the time delay from the once-per-rev signal to the rotor blade passage of interest. Since the rotor speed cannot be precisely maintained, the once per rev signal permits an error correction for the timing electronics on each rotation of the rotor.

The types of sensor systems used for generating a once-per-rev signal are hall effect sensor, laser diode/photodiode, and fiber optic probes. Part of the sensor is mounted on the rotor shaft (magnet, or reflective target) and the sensing element detects the passage of the rotor marking. All of these sensor systems create an analog signal which must typically be converted into a TTL logic signal for triggering the timing delay electronics.

IMAGE ACQUSITION AND PROCESSING

The primary factors influencing the choice of image acquisition and processing techniques are equipment availability and cost. For the purposes of this discussion efficiency of rig run time, maximum flexibility in image manipulation and storage, and optimal data processing will be considered the most important factors in determining the image acquisition and data processing strategies employed.

Photographic film offers the highest spatial resolution image measurements, which will appear to be the case for the near future, until digital cameras reach the resolution levels of photographic film. Electronic image acquisition has several advantages such as: real time feedback of the flow seeding conditions; optimization of the laser inter-pulse timing; image focusing; on-line assessment of flare light from blade surfaces and simplified data archiving and storage (image files instead of photographic film). A judicious choice of the camera field of view can result in acceptable levels of spatial resolution. CCD cameras with 1000×1000 pixels sensors can image a 50×50 mm field of view with 50 μm/pixel resolution. Assuming 32×32 pixel processing subregions, with 50% overlap yields a velocity vector grid with approximately 1.6 mm spatial resolution. In cases where larger fields of view are required and/or high resolution CCD imagers are not available, then photographic film may be the only acceptable choice.

The next choice, which again depends on the type of image recording system employed, is the image recording scheme: multiple exposure single frame images; or pairs of single exposure image frames. Multiple exposure (≥ 2) single frame images require auto-correlation data reduction, which places restrictions on the minimum displacement allowed between image exposures. The particles must displace by at least twice their diameters in order to achieve good correlation results. Image shifting (either electronic or mechanical mirror) can be used to resolve the directional ambiguity typically encountered in auto-correlation processing and to eliminate the minimum displacement requirement just described. However, the speed of the image shifting system must be at least an order of magnitude higher than the speed of the flow being measured.

The second, more favorable option for data acquisition and processing are a pair of single exposure image frames and cross-correlation processing. Refinement of the vertical drive period straddling technique first demonstrated by Wernet, 1991 has led to the development of commercial PIV cameras which permit a pair of image frames to be acquired with a very small inter-frame period (<1 μsec). The cameras employed are standard RS-170, 60 fields/sec video cameras or high resolution full frame CCD imagers running at 30 frames/sec. Both systems offer inter-frame exposure intervals of 1/30 sec down to < 1 μsec. Cross-correlation data reduction is the optimal data reduction technique for PIV since it offers directionally resolved velocity vectors, no self correlation peak and hence no restriction on the minimum particle displacement between exposures (the relative accuracy of the velocity measurements is inversely proportional to the displacement between exposures, therefore a reasonable displacement is desirable).

In general, averaging the velocity measurements obtained from several hundred PIV images should be of higher accuracy than the results obtained via LDV. Each PIV measurement realization is spatially averaged, and provided the seed density is sufficiently high, yields a nominal accuracy of approximately 1%. This level of accuracy is seldom achieved with LDV systems. Averaging the results from several hundred image frames will lower these errors by more than a factor of 10, yielding accuracies which are significantly higher than those obtainable with LDV, and yet the total acquisition time for the PIV data is more than an order of magnitude shorter.

In some instances, the turbomachinery flow fields under study may have a substantial out of plane velocity component. Loss of particles from the first to second exposure results in a loss of correlation, and thus data dropout. However, the out of plane velocity component can be tolerated by first increasing the thickness of the light sheet and second by shortening the time between exposures. Both of these modifications will increase the error in the measured velocities, but at least will enable a measurement.

Another advantage to using electronic image capture in PIV image acquisition has to do with correction of the images from window distortions. In many cases the optical access ports used to record the PIV image data are curved to match the inside diameter of the turbomachine casing. Image capture through these curved windows results in image distortion. By recording a reference image of a calibration target with a Cartesian grid of points, a set of image warping coefficients can be computed to correct for the effects of the window distortion. The image warping is readily applied to the digital imagery, but is not so straightforward when photographic recording is used.

Flare light reaching the CCD camera can cause significant amounts of blooming, leaving large areas of the imaged field useless. In lab scale facilities some of the compressor components can be fabricated from plexiglas to permit optical access and reduce flare light. However, the use of plexiglas in large scale, high speed machines is not feasible. Instead, other techniques must be used for minimizing the flare light reaching the CCD camera. Aligning the light sheet along the blade stagger angle minimizes the intersection area of the light sheet with the blade surface, hence, significantly reducing the amount of surface flare light. Painting the rotor hub and blades black also significantly improves the signal to noise ratio in the recorded images. Some flare light from the blade surfaces is desirable for referencing since it marks the position of the blade leading edge/surface in the recorded images. When all else fails, black tape can be placed on the optical access port window to block flare light caused by the light sheet hitting the blade surfaces. The proper placement of the tape on the window can be done at low speed using the appropriate time delay from the once-per-rev signal to stop the rotor at the same circumferential position each time an image is acquired. The time delay is then adjusted to stop the rotor in the same position when operating at design speed.

COMMERCIAL PIV PROCESSING SYSTEMS

In the early stages of development the PIV technique was implemented on a custom basis, where each installation was uniquely configured for both data acquisition and data reduction. Slowly the transition from film based acquisition and optical data reduction was made to electronic image capture using CCD cameras and framegrabber hardware and digital computer based data processing. The transition to digital data processing was especially slow since the requisite computing power did not exist for processing the image data via Fast Fourier Transforms (FFTs) in a reasonable amount of time. A single film exposure could have taken several days to completely process even with the aid of specialized array processing hardware.

As an interim solution, Particle Tracking Velocimetry (PTV) evolved where instead of performing correlation processing on small subregions on the image frame, individual particle images were tracked. The particle tracking operation proved to be a computationally simple process for PCs. Further improvements in computer processing power and the development of dedicated hardwired data processing chips have brought the correlation processing technique into the mainstream where the data processing can now be performed by a "turnkey" system. The image acquisition and seeding of the flow field has been and most likely will continue to be an obscure art form.

The software support offered in the most recently available commercial PIV systems is truly impressive and very user friendly. A thorough understanding of the basic concepts involved in correlation processing is still necessary in order to acquire and process meaningful data. The menu based data acquisition and processing systems simplify many of the often tedious tasks of acquiring, archiving and processing PIV imagery. These systems also control all of the laser timing and camera exposure timing and permit the use of external trigger signals for application to short duration phenomena or rotating machinery. One of the most interesting features is the ability to display the subregion currently being processed and the resulting correlation plane result - for this information is invaluable to the researcher in assessing the quality of the data being processed. By inspecting the input and output of the correlation process the researcher can learn valuable information about the experiment: adequate seed particle concentration; excessive flare light; excessive background noise. The processing power and information available to the user from these commercial PIV systems is truly amazing.

The main benefit of these commercial PIV systems stems from their ability to provide real-time, or very nearly real-time velocity vector maps from the acquired imagery by using electronic cameras and fast data processing. The electronic image acquisition and real-time processing of the acquired imagery provides immediate feedback to the experimenter on the quality and uniformity of the flow seeding, the appropriateness of the selected inter-pulse exposure interval and laser power level. Once the experimental parameters have been "tweaked" the data acquisition system can be configured to acquire a series of data sets so that average flow properties can be computed.

For the acquisition of images from facilities with high overhead costs, PIV systems which allow fast acquisition and storing of the acquired digital images are most desirable. Fast processing of the data is not important once the experimental parameters have been optimized; however, archiving the original image data is extremely important. The processing parameters selected during the initial setup may not prove to be the best settings for achieving the maximum information recovery from the raw PIV images. Archiving all of the raw image data permits the investigation of spurious results in the processed vector fields. Without the raw image files there is no way to discern the real cause of spurious vectors. Additional image processing steps may be required to maximize information recovery in regions of the image where noise levels are high, or particle concentrations are low. Finally, future improvements in data processing algorithms and techniques may permit better data extraction. For all of these reasons, storing the original image files is desirable and may save the expense of having to rerun the experimental tests.

PIV MEASUREMENTS IN A TRANSONIC COMPRESSOR

The study of the complex flow fields encountered in turbomachinery necessities the use of 3-component velocity measurements to fully resolve the flow field features. On the road to development of a 3-component measurement capability we have initiated a 2-D PIV measurement program in a transonic compressor. Some preliminary results from that research program will be presented. The plan is to eventually make 3-component, planar PIV measurements in both a high speed axial and centrifugal compressors.

The facility used in the study is a 50.8 cm diameter, single stage axial compressor with a design speed of 17,188 rpm and a mass flow rate of 20.19 kg/s. The rotor has 36 blades which are 75 mm tall at the leading edge and 56 mm at the trailing edge. The blade stagger angle is 41° at the hub and 61° at the tip. The casing is fitted with a large optical access port (200×100 mm) which is molded to the complex contour of the casing. The glass thickness is 3 mm and produces a very small amount of optical distortion. None of the optical distortion effects will be considered here.

The seeding was provided by a 6 jet atomizer which was coupled through the rig housing via 6 mm diameter tubing approximately 60 tube diameters upstream of the rotor. The seeding probe position could be adjusted radially to provide seed in the plane of illumination. The light sheet was introduced into the rig via a NASA-designed and built optical periscope probe depicted in figure 3a. The light sheet delivery probe outside diameter was 12.7 mm, and 8 mm diameter light sheet forming optics (200 mm focal length spherical and -25 mm focal length cylindrical lenses) were used inside. The probe was inserted through the casing at a circumferential position 45° down from the rig centerline and approximately 200 mm upstream of the rotor. The inclination angle of the light sheet roughly matched the blade stagger angle at mid span. The light sheet generated by the probe was approximately 45 mm wide and 1 mm thick at the measurement location. A commercial articulated light arm was used to couple the light from a pair of Nd:YAG lasers to the periscope probe. The Nd:YAG light sheet pulse energy was approximately 125 mJ/pulse. A schematic representation of the optical system implementation in the compressor rig is depicted in figure 3c.

A commercial PIV system running on a PC was used to collect and analyze the data. No array processing hardware was required. A 1000×1000 pixel cross-correlation CCD camera utilizing frame straddling was used to acquire the imagery. The camera image acquisition and laser firing were all software controlled via a commercial synchronizer. Correlation processing was used to initially verify that sufficient seed particles were present and that the appropriate laser inter-pulse timing had been selected. After the initial experiment setup was complete, raw PIV images were acquired directly into the PC's memory and then saved directly to disk without processing the images. Correlation processing of the images was performed later after the experiment was completed. The image acquisition rate was 10 frames pairs/sec (limited by the Nd:YAG laser repetition rate) and the time to store each image to disk was approximately 1 second. This data acquisition mode minimized the rig run time and offered maximum flexibility in the selection of the appropriate post processing of the acquired images.

A once-per-rev signal on the rotor was used to trigger image acquisition and laser firing. The minimum inter-frame time achievable with the cross-correlation camera system was approximately 1.1 μs due to some jitter in the once-per-rev signal. For experiments where the PIV system provided the master timing, inter-frame times down to 300 nsec have been achieved. For the measurements reported here the inter-frame delay time was 2.67 μs. The camera image scale factor was 56 μm/pixel, yielding roughly a 56x56 mm field of view. The light sheet illumination covered most of a blade passage in the circumferential direction at a passage height of 46 mm from the hub. The plane of the light sheet intersected the lower blade at constant radius, but was slightly inclined along the pressure surface of the upper blade.

A single exposure raw PIV image is shown in figure 4a and the computed velocity vector field in figure 4b. Figure 4a shows the relative positions of the blades and the level of particulate seeding. Tape has been placed on the windows to reduce the flare light scattered off of the blade surfaces. The vectors in figure 4b are scaled in proportion to velocity vector magnitude and also color coded by vector magnitude. The correlation subregion size was 64x64 pixels with approximately 50% overlap. Spurious vectors have been removed from around the blade surfaces and in the periphery of the image. No interpolation or data filling has been applied. The compressor was operated at 17,128 rpm and a mass flow rate of 20.14 kg/s, yielding a pressure ratio of 1.86. The flow velocity upstream of the rotor is 190 m/s and the blade tip speed is 455 m/s. The flow direction is from left to right and the rotational direction is from top to bottom. The blade profiles at the measurement plane location are shown in the figure. Under these rig operating conditions a shock wave forms off the blade leading edge and spans the blade passage. A bow wave also forms off of each blade extending outward (up and to the left) from each blade tip. The measurements are shown in absolute velocity and the position of the blade-to-blade plane shock is readily observed by the sharply turning vectors in figure 4b. The flow turns sharply downstream of the shock as it now feels the influence of the shock generated by the rotor. The bow wave from both the lower and upper blade rows are also

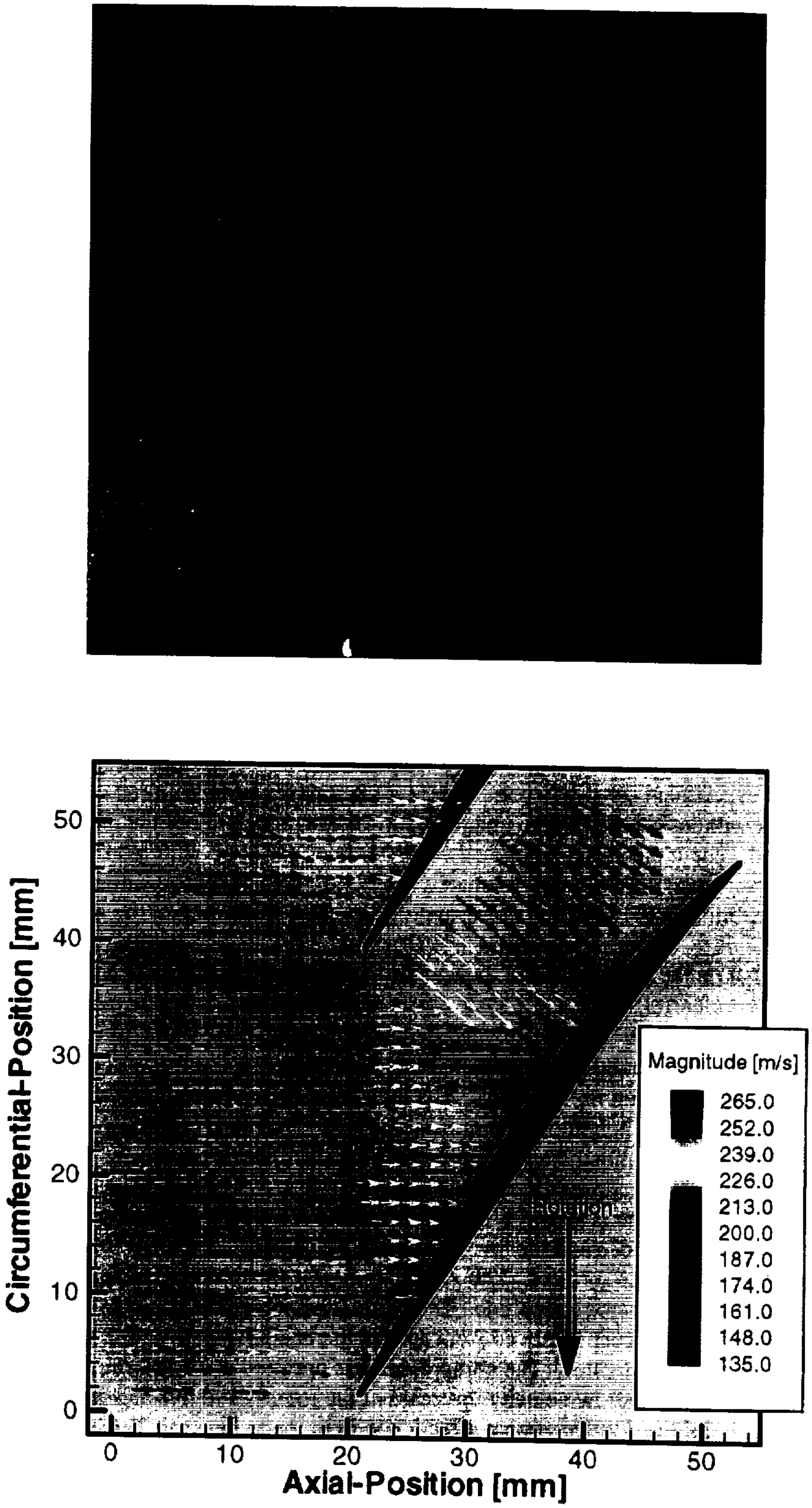

Figure 4: a) Raw single exposure CCD camera image of seed particles in compressor flow, tape has been placed on the casing window over the blades to block surface flare light; b) Processed vector field from image shown above, note the bow waves off of the leading edges of the blades and the blade-to-blade shock (vectors shown in absolute reference frame).

observed in the left portion of the image. There is a significant change in velocity magnitude and a small change in vector angle across the bow waves as indicated by the color shading and the direction of the vectors, respectively.

CONCLUSIONS

Recent advances are leading to the emergence of Particle Imaging Velocimetry as a powerful velocity measurement technique which can be used as an alternative or complementary approach to LDV in a wide range of research applications. Commercial PIV processors have matured to the point where they have simplified the data acquisition and reduction of PIV imagery to a "turn key" operation. Many of the same concerns and issues encountered in applying LDV to rotating machines apply to the successful implementation of PIV. The remaining challenges in the application of PIV to rotating machinery of introducing the light sheet into the facility, seeding and optical access for image recording are surmountable as demonstrated here. Successful PIV measurements have been obtained in a transonic compressor yielding instantaneous snapshots of the complex turbomachinery flow. The preliminary results shown here demonstrate that the PIV technique yields fast and accurate velocity information. The measurements obtained here in just a matter of seconds have previously taken several hours to obtain via LDV in similar facilities. The PIV results display large sections of the flow field structure in very short rig operation times. Future work will concentrate on using PIV to investigate rotor blade trailing edge vortices, flow separation off of the blades, and then extension of the 2-D PIV technique to obtain planar 3-component velocity measurements via a two camera, stereo viewing arrangement.

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Particle Imaging Velocimetry (PIV) is emerging as a powerful measurement technique which can be used as an alternative or complementary approach to Laser Doppler Velocimetry (LDV) in a wide range of research applications. The instantaneous planar velocity measurements obtained with PIV make it an attractive technique for use in the study of the complex flow fields encountered in turbomachinery. The data acquired offer several advantages over traditional LDV data: higher accuracy; multiple measurement points and the ability to study both transient and steady state flow phenomena. Many of the same issues encountered in the application of LDV techniques to rotating machinery apply in the application of PIV. Techniques for optical access, light sheet delivery and particulate seeding are discussed. Preliminary results from the successful application of the PIV technique to a transonic axial compressor are presented.

14. SUBJECT TERMS

Particle imaging velocimetry; Rotating machinery; Turbomachinery; Compressor; Transonic; Correlation processing; Light sheet; Periscope

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